CHARACTERIZATION OF STRUCTURAL CONNECTIONS

FOR MULTICOMPONENT SYSTEMS

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ABSTRACT

The inability to adequately model connections has limited the ability to pre-
dict overall system dynamic response. Connections between structural compo-
nents are often mechanically complex and difficult to model analytically.
Improved analytical models for connections are needed to improve system dynamic
predictions. This research explores combining component mode synthesis methods
for coupling structural components with parameter identification procedures
for improving the analytical modeling of the connections (Hucklebridge, 1987;
and Lawrence, 1988). Improvements in the connection stiffness and damping
properties are computed in terms of physical stiffness and damping parameters,
so the physical characteristics of the connections can be better understood,
in addition to providing improved input for the system model.

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Analytical models of structural systems do not normally produce characteristics that agree with those obtained from experiments. The discrepancy can often be attributed to structural properties such as connection damping and stiffness, which are extremely difficult to characterize, while their influence on structural response predictions is profound.

OBJECTIVE

- DEVELOP IMPROVED ANALYTICAL MODELS FOR STRUCTURAL CONNECTIONS

- IDENTIFY CONNECTION STIFFNESS AND DAMPING PROPERTIES FROM SYSTEM MODAL DATA

- DETERMINE CONNECTION PROPERTIES IN TERMS OF PHYSICAL PARAMETERS

- USE SUBSTRUCTURING METHODS FOR MODELING EFFICIENCY AND INCORPORATION OF MODAL COMPONENTS
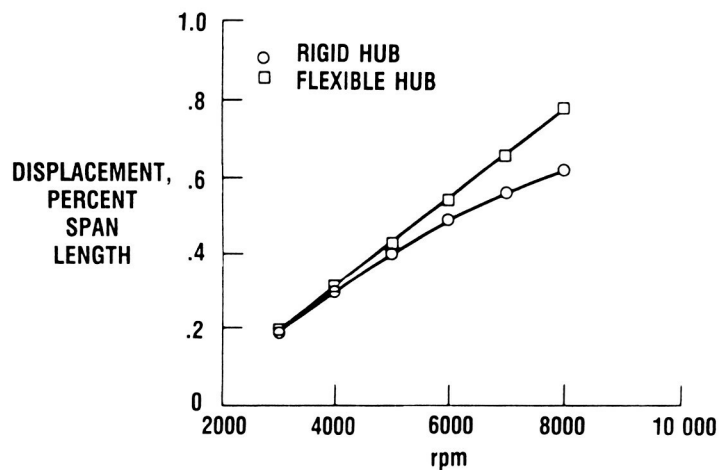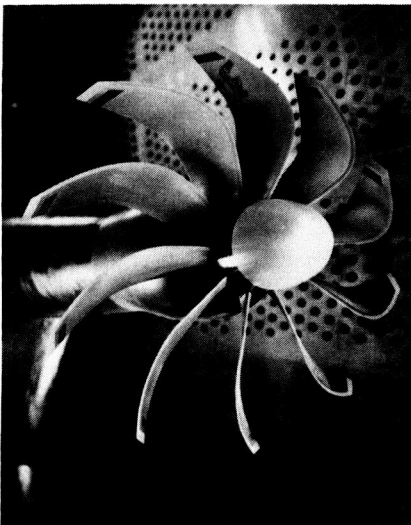
APPROACH

- DEVELOP COUPLED SYSTEM EQUATIONS FROM "MIXED" SUBSTRUCTURES

- OBTAIN BOTH PREDICTED AND MEASURED MODAL DATA FOR SYSTEM

- MINIMIZE DIFFERENCE BETWEEN MEASURED AND PREDICTED SYSTEM CHARACTERISTICS BY OPTIMAL SELECTION OF CONNECTION PARAMETERS

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JOINT STIFFNESS EFFECTS ON DISPLACEMENTS

The effect of connection flexibility on steady-state displacements, and frequencies and mode shapes, was assessed for the GE-A7-B4 advanced propfan blade. Results indicate that connection flexibility is significant, and in order to insure accuracy, connection flexibility must be precisely characterized.

GE-A7-B4 LEADING EDGE TIP DISPLACEMENTS.
RIGID HUB VERSUS FLEXIBLE HUB

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The approach used for developing the coupled system equations of motion used component models represented through the use of finite elements or with modal data. Component modal data may be obtained from experiment or from a reduced finite-element model. Once the system equations of motion are constructed, they can be used to predict the system frequencies and mode shapes. These modal data are then used in conjunction with the experimentally measured modal parameters to identify the connection properties.

U^I **DISPLACEMENT DEGREES OF FREEDOM (DOF) FOR COMPONENT I**

U^{II} **DISPLACEMENT DOF FOR COMPONENT II**

U^C **DISPLACEMENT DOF FOR CONNECTION**

b **BOUNDARY DOF**
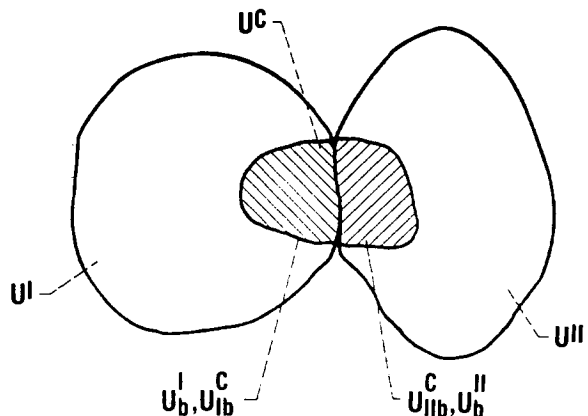
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Parameter identification methods that incorporate optimization strategies can be classified into three groups: least squares, weighted least squares, and Bayesian estimation. With the least squares method, the set of parameters that minimizes the difference between the measured and predicted response is computed. The weighted least squares method incorporates a weight, indicating the relative confidence in the measured data. The Bayesian method permits specification of the randomness of the connection parameters as well as the confidence in the measured data.

THE WEIGHTED SQUARED DIFFERENCE BETWEEN THE PREDICTED AND MEASURED CHARACTERISTICS IS

$$\{F\} = [W] \left(\{\bar{C}\} - \{C\} \right)^2$$

SETTING THE DERIVATIVE TO ZERO AND EXPANDING THE PREDICTED SYSTEM CHARACTERISTICS IN A TAYLOR SERIES, THE CONNECTION PROPERTIES ARE SOLVED FOR ITERATIVELY FROM

$$\{r\} = \{r\}_{EST} + \left([S]^T [W] [S] \right)^{-1} [S]^T [W] \left(\{\bar{C}\} - \{C\}_{EST} \right)$$

$\{\bar{C}\}, \{C\}$ MEASURED AND COMPUTED SYSTEM FREQUENCIES AND MODE SHAPES

$[W]$ WEIGHTING MATRIX

$[S]$ $\partial\{C\}/\partial\{r\}$

$\{r\}$ CONNECTION STIFFNESSES AND DAMPING

SYSTEM DYNAMICS PARAMETER IDENTIFICATION PROGRAM

A general FORTRAN computer code was developed for incorporating the component coupling and parameter identification procedures. Components are represented by fixed or free interface modes and can include residual flexibilities. Coupling is through flexible or rigid connections. Damping is added to the system through the use of viscous dampers. The experimental data used for the parameter identification include complex eigenvalues (frequency and damping) and mode shape values.
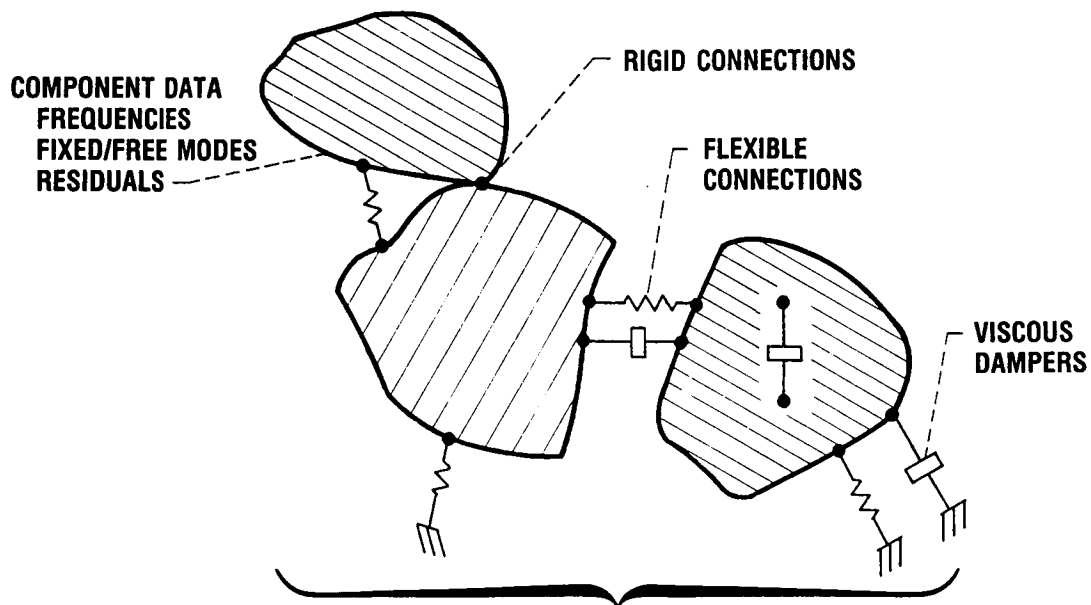

EXPERIMENTAL FREQUENCIES, MODAL DAMPING, MODE SHAPES, AND WEIGHT FACTORS

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ROTATING STRUCTURAL DYNAMICS RIG

The rotating structural dynamics (RSD) rig at NASA Lewis was used to evaluate
the component coupling and parameter identification algorithms. The RSD rig,
which was designed to simulate actual engine structures, is used to study
active rotor control and system dynamics (component interaction) problems.
The rig components, although considerably simpler than a real turbine engine's
compounds, were scaled to simulate an actual engine's structural dynamics
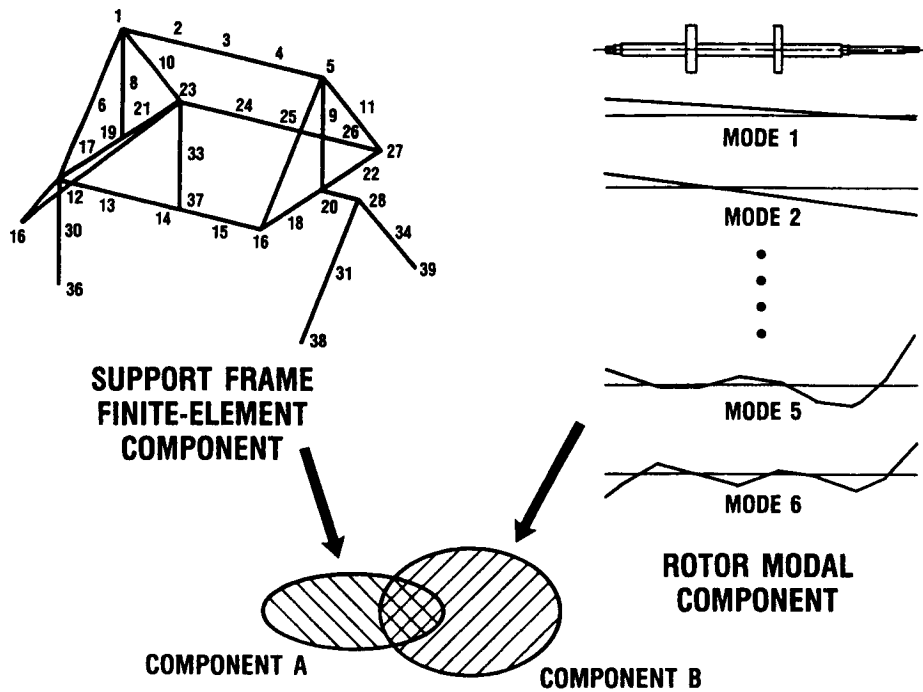response characteristics.
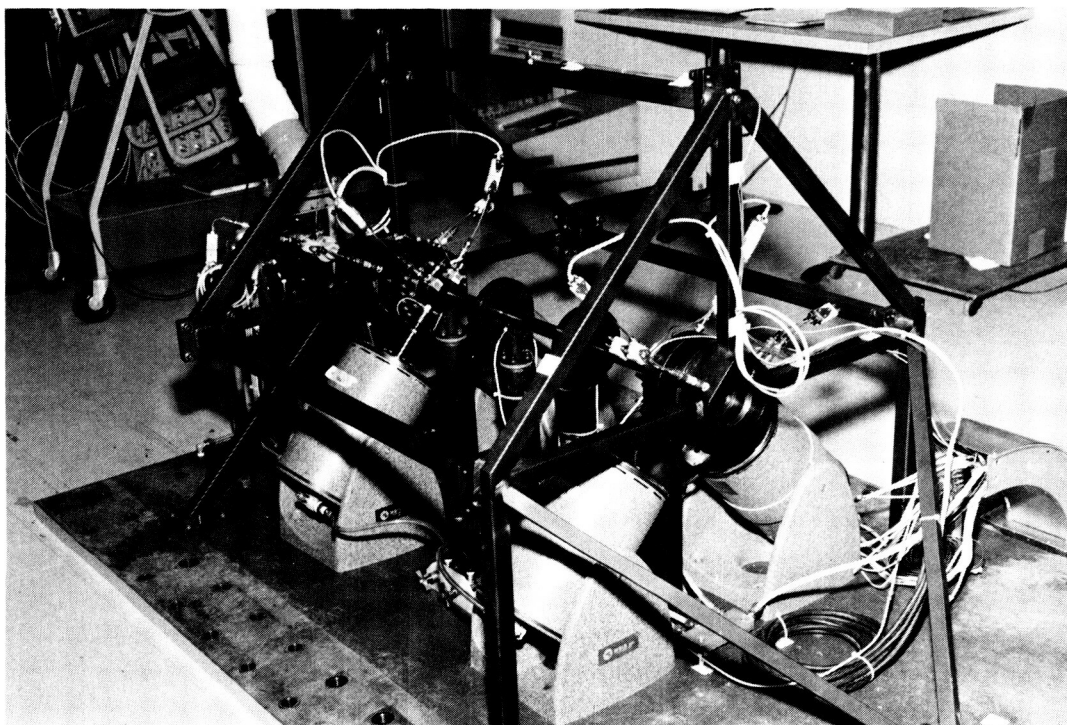
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The objective of the parameter identification was to determine the stiffnesses of the bearing support that connects each end of the rotor to the support frame. To accomplish this, the RSD rig was divided into two components: the rotor support frame, and the rotor.

**SUPPORT FRAME
FINITE-ELEMENT
COMPONENT**

MODE 1

MODE 2

MODE 5

MODE 6

**ROTOR MODAL
COMPONENT**

COMPONENT A

COMPONENT B

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COUPLED SYSTEM ANALYSIS

The coupled system frequencies are plotted along with the measured frequencies. The predicted frequencies were computed for different values of bearing support stiffness to determine the effect that the supports have on the system frequencies. When three system frequencies are used, the cage stiffness is identified as 5750 lb/in. This value is in good agreement with the measured stiffness of 5050 lb/in.
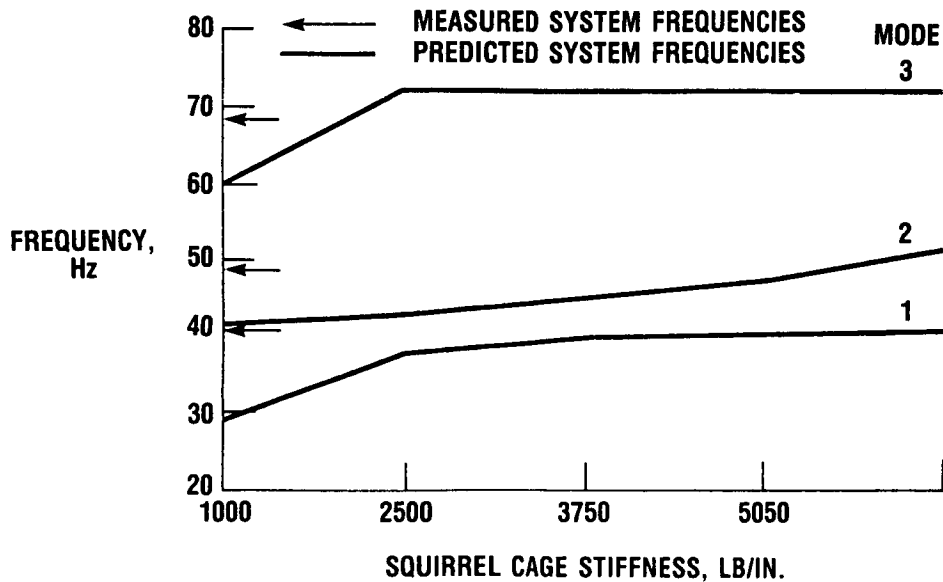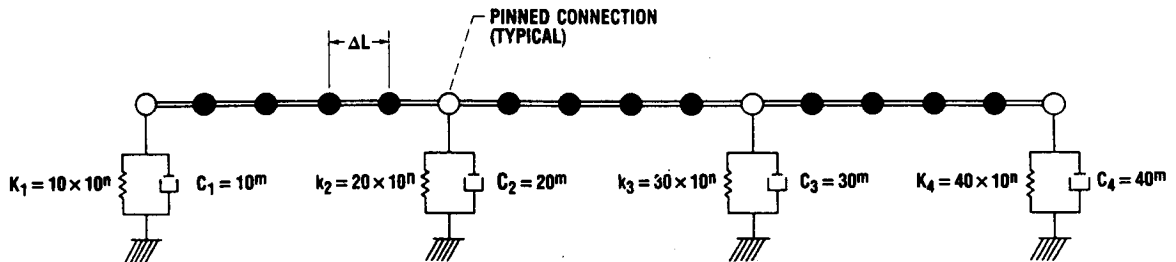

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This sample problem is presented to demonstrate identification of connection damping. For this problem a finite-element model was used to generate simulated experimental data. The model consists of three planar elastic beams connected at their ends with revolute (pinned) connections. Each of the connections is connected to ground by linear, translational springs and viscous dampers.

THREE COMPONENT COUPLED SYSTEM ($EI = 10^5$, $\rho = 0.10$, $\Delta L = 1.0$)

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DIFFERENCES BETWEEN COMPUTED AND EXPERIMENTAL PROPERTIES
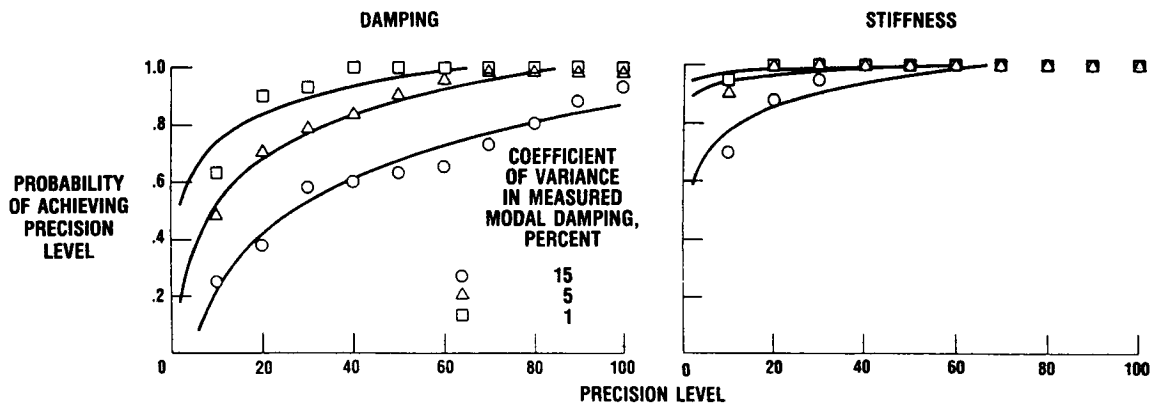
Damping and stiffness connection properties were identified for a range of damping levels. The flatness of the curves demonstrates the insensitivity of the identified connection stiffness and damping to the level of damping. Even near critical damping, the properties are computed accurately.
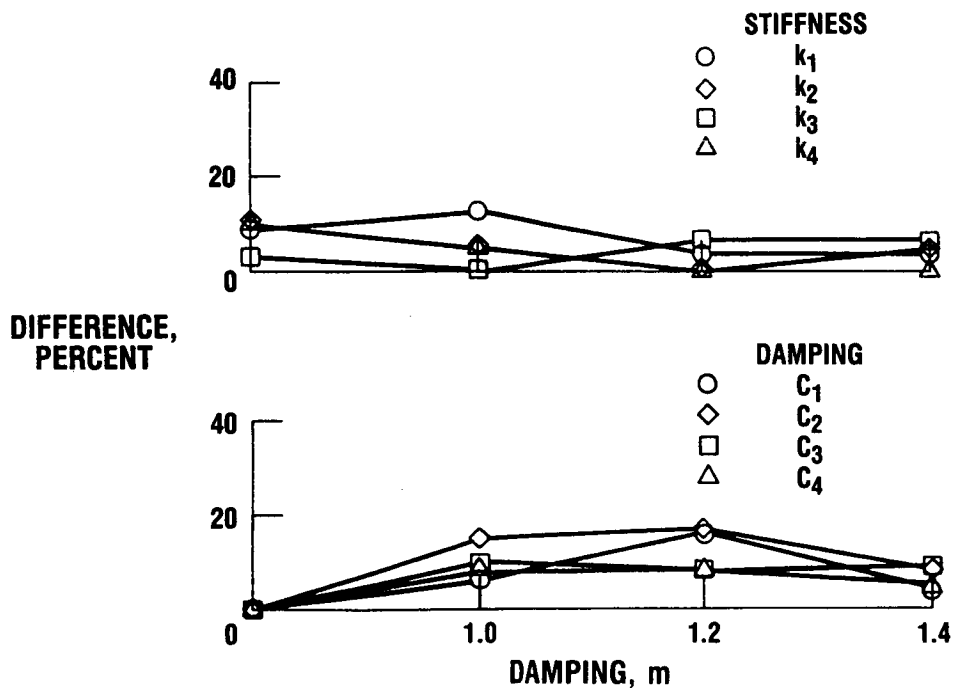
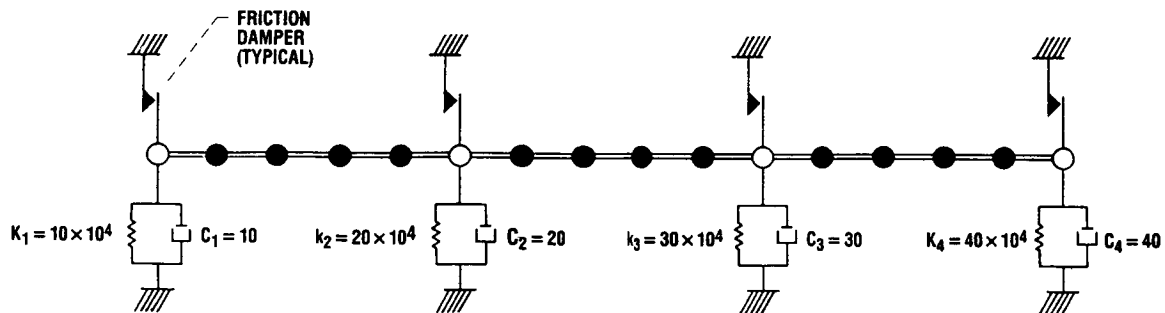CD-88-31852

ASSESSMENT OF EXPERIMENTAL ERROR

A Monte Carlo simulation was used to assess the accuracy of the parameter iden-
tification for various degrees of experimental error. Plots displaying the
probability of achieving a precision level are shown below. As the deviation
in the measured data increases, the probability of achieving a given level of
precision decreases.

DAMPING   STIFFNESS

PROBABILITY
OF ACHIEVING
PRECISION
LEVEL

COEFFICIENT
OF VARIANCE
IN MEASURED
MODAL DAMPING,
PERCENT

O	15
△	5
□	1

PRECISION LEVEL

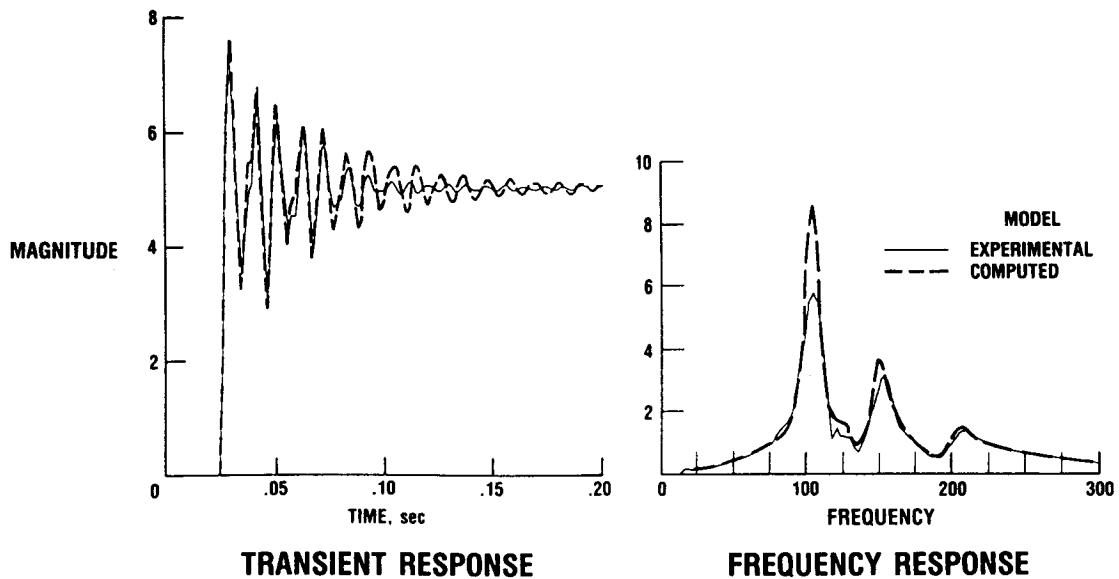CD-88-31853

THREE-COMPONENT SYSTEM WITH FRICTION DAMPING

The connections in many structural systems contain nonlinearities such as friction. For multidegree of freedom systems it is virtually impossible to identify and characterize all the complexities that can exist in the connections. Often, a simplifying assumption is made that the connection damping can be adequately described by linear viscous dampers even though other types of damping exist in the connection.

FRICTION
DAMPER
(TYPICAL)

$K_1 = 10 \times 10^4$ $C_1 = 10$ $k_2 = 20 \times 10^4$ $C_2 = 20$ $k_3 = 30 \times 10^4$ $C_3 = 30$ $K_4 = 40 \times 10^4$ $C_4 = 40$

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EVALUATION OF VISCOUS DAMPING MODEL

Equivalent viscous damping ratios were computed for various levels of friction damping. The performance of the identified models was assessed by comparing transient responses of the identified models to those from the experimental models. The responses from the identified and experimental models were evaluated by comparing peak response, settling time, and RMS error.

TRANSIENT RESPONSE   FREQUENCY RESPONSE

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SUMMARY AND CONCLUSIONS

Identification of structural dynamic systems is effectively performed by combining substructuring methods with parameter identification techniques. When substructuring methods, such as component mode synthesis, are used, the complexity of the identification problem is greatly reduced. Components and intercomponent structural connection properties are identified and evaluated independently, thus drastically decreasing the magnitude of the identification problem.

- **IDENTIFICATION OF STANDARD CONNECTION IS EFFECTIVELY PERFORMED BY COMBINING SUBSTRUCTURING METHODS WITH PARAMETERS IDENTIFICATION TECHNIQUES**

- **MODAL TEST DATA ARE EFFECTIVE FOR IDENTIFYING STIFFNESS AND DAMPING PROPERTIES OF COMPONENT CONNECTIONS.**

- **THE PARAMETER IDENTIFICATION IS IMPROVED WHEN THE QUALITY AND QUANTITY OF EXPERIMENTAL DATA ARE INCREASED.**

- **SMALL AMOUNTS OF NONLINEARITY CAN BE APPROXIMATED WITH VISCOUSLY DAMPED MODELS.**

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REFERENCES

Hucklebridge, A.A., and Lawrence, C., 1987, "Identification of Structural
    Interface Characteristics Using Component Mode Synthesis," ASME Vibrations
    Conference, Boston, MA, NASA TM-88960.

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    tural Connections for Multi-Component Systems," NASA TM-100801.